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13. ABSTRACT *(Maximum 200 words)*
An electric field propagating as a ground wave over finitely conducting ground suffers Ohmic loss, which increases with frequency. This loss is a function of the ground constants (conductivity and dielectric constant) and source height. Ground conductivities were estimated from waveshape differences in dE/dt pulses arising from different propagation distances. The data were wideband dE/dt signals recorded from five measurement sites stations at Kennedy Space Center. A model was used to introduce additional loss into the closer station waveshape so that it matched the more distant station waveshape. Up to four conductivities per dE/dt pulse were estimated via pairwise matches with the furthest station waveshape. The waveshapes were matched by using a gradient method to minimize the sum of the squares of the measurement residuals. The geometric mean of 96 ground conductivity estimates was 0.0042 S/m and the geometric standard deviation was 2.0. Both of these values are in line with published values. Errors arising from uncertainties in distance, height, and dielectric constant accounted for only 8% of this standard deviation. However, it was not clear whether the two-times spread was caused by system noise or an actual variation in conductivity. System noise was reduced for a handful of pulses by estimating a single conductivity per pulse via the pairwise matching of station data all possible pairs.

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Ground conductivity estimated from wideband dE/dt waveshapes of distant lightning sources near ground

ABSTRACT

An electric field propagating as a ground wave over finitely conducting ground suffers Ohmic loss, which increases with frequency. This loss is a function of the ground constants (conductivity and dielectric constant) and source height. Ground conductivities were estimated from waveshape differences in dE/dt pulses arising from different propagation distances. The data were wideband dE/dt signals recorded from five measurement sites stations at Kennedy Space Center. A model was used to introduce additional loss into the closer station waveshape so that it matched the more distant station waveshape. Up to four conductivities per dE/dt pulse were estimated via pairwise matches with the furthest station waveshape. The waveshapes were matched by using a gradient method to minimize the sum of the squares of the measurement residuals. The geometric mean of 96 ground conductivity estimates was 0.0042 S/m and the geometric standard deviation was 2.0. Both of these values are in line with published values. Errors arising from uncertainties in distance, height, and dielectric constant accounted for only 8% of this standard deviation. However, it was not clear whether the two-times spread was caused by system noise or an actual variation in conductivity. System noise was reduced for a handful of pulses by estimating a single conductivity per pulse via the pairwise matching of station data all possible pairs.

EXPERIMENT

The measurement system comprised five sensing stations in a network approximately 15 km x 15 km in size at Kennedy Space Center, Florida. The stations were located at the Shuttle Landing Facility (SLF), the eastern bank of the Indian river, the Universal Camera Site on Playalinda Beach (UC9), the Engineering Development Laboratory (EDL), and the Unified S-Band site (USB), as shown in the map of Fig. 1. In the following analysis, we refer to these as stations 1 through 5 respectively. The Indian River, Banana River and Atlantic Ocean all had conductivities of about 4 S/m. The Indian River and UC9 sensors were sited on well-conducting salt marsh (conductivity of about 2 S/m) while SLF, EDL, and USB were sited on stratified sand dunes with conductivities that we determine to be of the order of 10^{-2} S/m.

The time derivative of the electric field, dE/dt was detected at each station by sensing the displacement current intercepted by a flat plate antenna. Gains from unity to 450 were achieved with different combinations of plates and amplifiers. Calibration signals were applied through a known resistance directly to the inputs of the dE/dt amplifiers to simulate a known dE/dt. The calibration signals included a square wave for absolute sensitivity determination, a triangle wave for linearity and saturation levels, an impulse (< 20 ns half width) and fast (< 30 ns 10-90% risetime) square wave for frequency response, and a horizontal synch pulse from Channel 35 TV in Orlando for timing. All gain and calibration controls were remotely controllable from the central recording station via two-way audio signals. Each dE/dt sensor plate was placed near the center of a 3.5 m x 3.5 m conducting

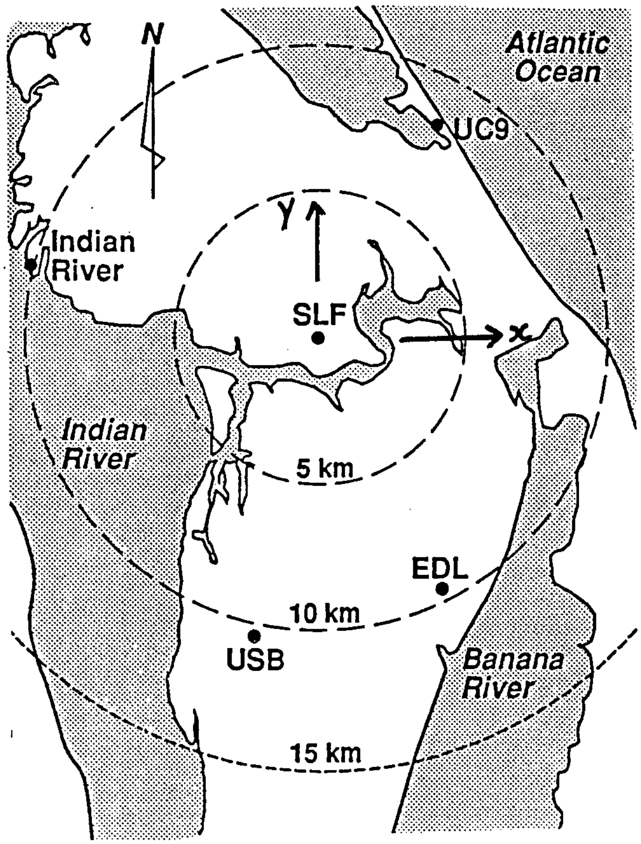

Figure 2 Sensor station layout

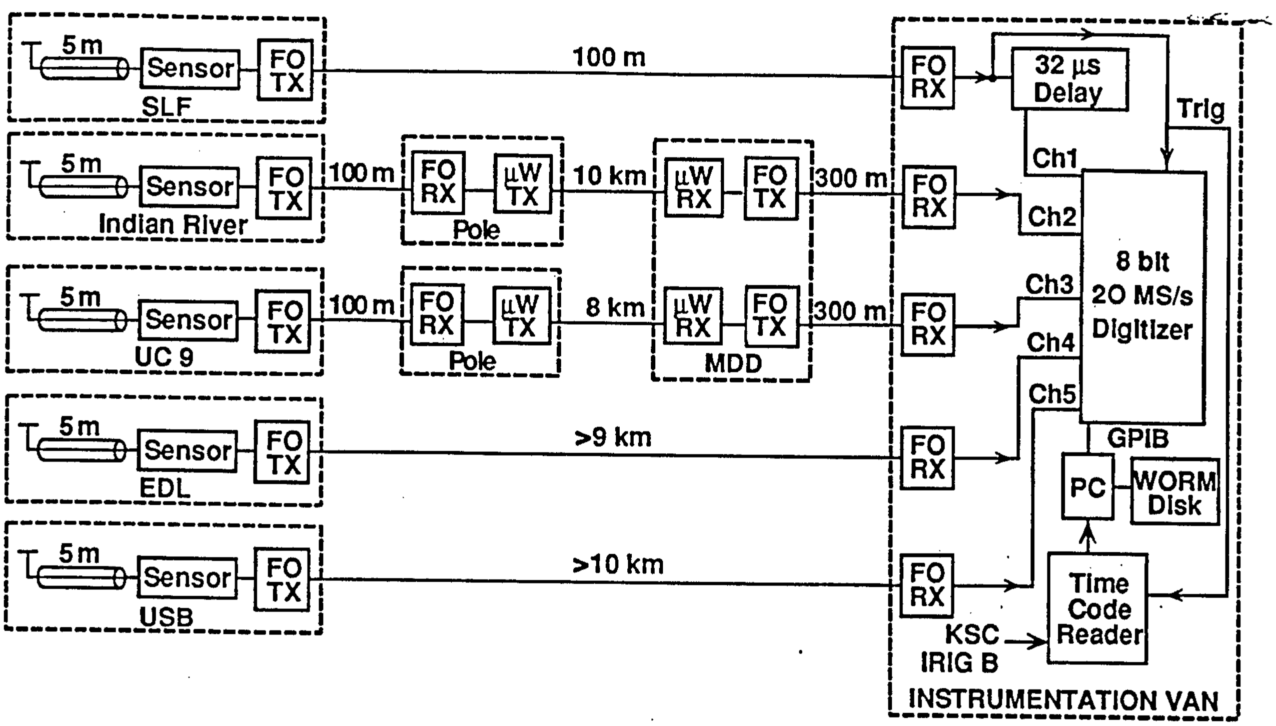

Figure 1 Signal links and recording system

ground plane raised .5 m above local ground. The plates were connected to the sensor electronics, placed in a shielded box at one corner of the ground plane, via shielded 50 Ω coaxial cables routed below the ground plane. All signals passing to and from this box were electrically isolated from subsequent signal and communication links with fiber optics and optoisolators. Fig. 2 is the block diagram showing the signal paths from these remote ground planes. Signals were sent back to the central recording station, that was 100 m away from the SLF ground plane, via either microwave links with a carrier of 10 GHz and 3 dB bandwidth of 1 Hz to 8 , or analog fiber optics links with a 3 dB bandwidth of 1 Hz to 14 . The signals were recorded at the central station in digital form using a 5-channel 8-bit Le Croy digitizing system interfaced with an 80386-based IBM clone PC. The signals were digitized at a rate of 20 MS/s for a duration of 200 μs each time a trigger event occurred at the central station. A trigger time, derived from Kennedy Space Center IRIGB with 1-μs resolution, corresponded to the start of the 200-μs recording window for each trigger event. Consecutive trigger events were digitized sequentially with a 40-μs dead time between windows until the 128 kS Le Croy memory was full. Twenty five trigger events could be recorded per lightning. A dead time of 1.5 s resulted when the digitized data for a 25-event lightning was transferred from Le Croy memory to computer RAM; hence, the initial pulses from virtually all lightnings in a storm could be recorded. Channel 1, corresponding to the sensor site at SLF, had a 32 μs pretrigger delay so that pretrigger data could be recorded and the inherent delays in the signal links for the other channels meant that the signal radiated by the event that triggered the system was recorded somewhere in the 200 μs window. The digital design of the 32-μs delay in Channel 1 necessitated an additional anti-alias filter that reduced the frequency response of this channel to a 6-dB cutoff frequency of about 2 ; the other channels had a 6-dB cutoff frequency of about 4 . The digitizing system was activated 24 hours per day, with data being stored initially on a 1GB Winchester disk and later archived on optical disks

THEORY

Because of finite conductivity of ground, attenuation occurs when a horizontally polarized electromagnetic ground wave propagates at grazing incidence. The penetration into the ground of the surface current (upon which tangential H terminates) causes the e-m wave to be attenuated via Ohmic losses. Since the ground is both a dielectric and a conductor, it is penetrated more readily by the higher frequency components of the spectrum; thus, it acts as a lowpass filter. Maxwell's equations for E and H are duals in the absence of free charge, so the attenuation function for E, from attenuation by Ohmic losses due to the penetration of E into the finitely conducting ground, is the same for horizontally polarized e-m waves as it is for vertically polarized e-m waves; however, this paper assumed that lightning channels and E were vertical, so that there was no possibility of time dilation effects.

For an electric dipole having moment $p_0 e^{-i\omega t}\hat{z}$ oriented along the z-axis in free space at point $(\rho, \varphi, z) = (0, 0, h)$ in cylindrical coordinates as shown in Fig. 3, the radiation electric field at distance R as a function of time t is (Wangsness, 1986, p. 479):

$$\vec{E} \approx -\frac{k^2 p_0}{4\pi\varepsilon_0 R} \sin\theta_R e^{i(kR-\omega t)} \hat{\theta}_R$$

in the plane z=0, where θ_R is the angle from the dipole to the field point $(\rho, 0, z)$ and where the propagation constant is $k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$ where λ is the wavelength and ω is the angular frequency. For example, in the transmission line model of Uman, et al. (1975), $E_R(\rho, t) = -(\mu_0 v / 2\pi\rho) i(t - \rho / c)$; $t \leq h / v + \rho / c$, where i is the lightning current, v is the velocity of propagation of the current wave along the transmission line, and h is the source height.

The vertical Hertz vector Π_z for an incremental vertical current source of length ds is used by Wait (1981, p. 117) to sketch a derivation of the Sommerfeld (1909, 1926) attenuation function F(w) below for $kR_1 >> 1$, the radiation zone. The Hertz vector includes a term for the direct ray and a term involving the reflection coefficient $R_{\|}(\lambda)$ of the ground:

$$\Pi_z = \frac{ids}{4\pi i\varepsilon_0 \omega} \int_0^\infty \left[e^{-u_0|z+h|} + R_{\|}(\lambda) e^{u_0(z-h)} \right] \frac{\lambda}{u_0} J_0(\lambda\rho) d\lambda$$

Wait (1971, pp. 165-167) sketches and resolves and gives the result for the Sommerfeld (1909, 1926) attenuation function F(w)

$$F(w) = 1 - i\sqrt{\pi w} e^{-w} erfc(i\sqrt{w}) \qquad (1)$$

where $w = p[1 + (z+h) / \Delta R_1]^2$, $p = -\frac{1}{2} ikR_1\Delta^2$ is the numerical distance,

$erfc(i\sqrt{w}) = \frac{2}{\sqrt{\pi}} \int_{i\sqrt{w}}^{\infty} e^{-z^2} dz$ is the complex error function,

$\Delta = \frac{Z}{\eta_0}$, $R_1 = \sqrt{(z+h)^2 + \rho^2}$ (refer to Fig. 3) is the distance from the source image to the observer, ρ is the horizontal distance from the source to the observer, h is the height of the source, z is the height of the station (assumed zero) and Z is the surface impedance. If $z << \rho$ and h = 0 then $R_1 \approx \rho$. Since Z=E/H, $\Delta = \frac{Z}{\eta_0} = \frac{ik}{\gamma_1} \sqrt{1 + \left(\frac{k}{\gamma_1}\right)^2}$ is the wavetilt for a plane wave at grazing incidence, where $\gamma_1 = \sqrt{\omega(i\sigma\mu - \varepsilon\mu\omega)}$ is the propagation constant of the ground, σ and ε are the conductivity and permittivity, respectively, of the ground, $\eta_0 \approx 377\Omega$ is the impedance of free space, and μ_0 is the permeability of either medium.

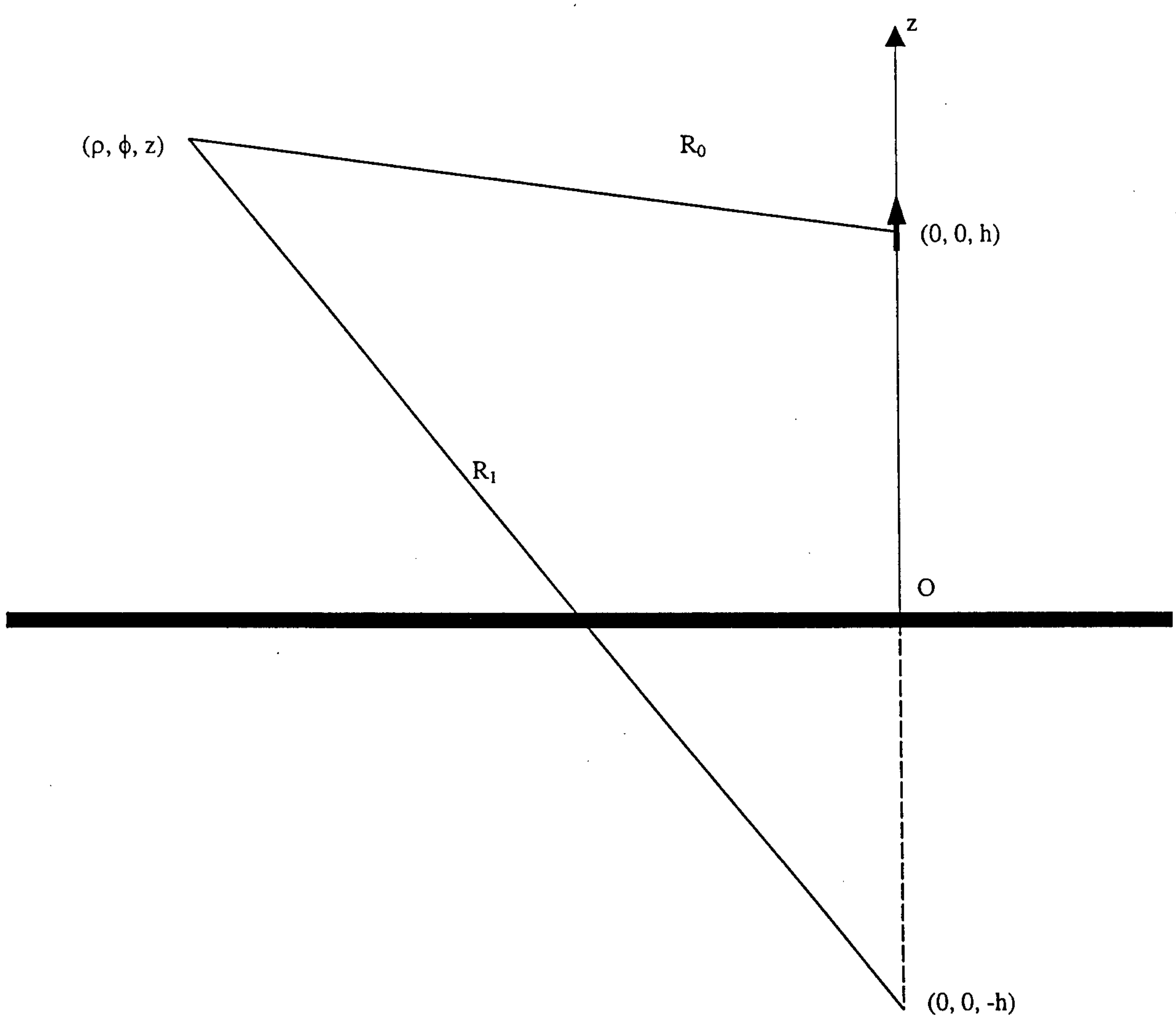

Fig. 3. Vertical source dipole at (0, 0, h) above finitely conducting ground and field point at (ρ, ϕ, z).

The estimate of the attenuation function for transforming a lightning dE/dt waveshape received at a nearby station to a further station is

$$\hat{G}(\sigma,\omega,h,d_f,d_n,K) = \frac{F(\sigma,\omega,h,d_f,K)}{F(\sigma,\omega,h,d_n,K)} \tag{2}$$

where $F(\sigma,\omega,h,d,K) = F(w)$ is Sommerfeld's (1909, 1926) attenuation function, ω is the angular frequency, d_f and d_n are the net propagation distances over land from the far and near stations to the source, respectively, and K is the dielectric constant.

If $\omega \neq 0$ then the measured attenuation function is

$$G(\omega) = \frac{\omega E_{far}(\omega)}{\omega E_{near}(\omega)} = \frac{E_{far}(\omega)}{E_{near}(\omega)} \tag{3}$$

i. e., the attenuation functions $G(\omega)$ and $\hat{G}(\omega)$ have the same form for dE/dt as for E.

All $\frac{1}{\rho}$ spreading losses for radiation fields and individual station gains are calibrated out.

A formula for the depth at which a lower layer of different conductivity will affect a conductivity estimate attributed to homogeneous ground is (Wait, 1981, p. 11):

$$d = \frac{3}{\sqrt{\sigma\mu\omega}} \tag{4}$$

Source heights exceeding one wavelength can affect conductivity estimates if zero height is assumed for the model, but the Sommerfeld (1909, 1926) attenuation curves showed little variation for heights less than one wavelength from ground even for frequencies around 2.0 MHz, which is the upper frequency limit of the spectra of the two lightning waveforms shown in Fig . 4 and Fig. 5. These plots are described in more detail in the Results section below. The sensitivity of attenuation with height is shown for five heights near ground in Fig. 6(a). The lightning pulses we chose for analysis have low altitudes: they are either return strokes pulses or stepped leader pulses within ten microseconds of a return stroke. Source heights (attachment points) of return strokes are probably about 30 meters or less. The radiation field of an upward lightning pulse propagating along a vertical transmission line can be estimated from a turn-on term near ground (Uman, et al., 1975). For stepped leader pulses within 10 microseconds of a return stroke and having velocities of $2 \cdot 10^7$ m/sec. or less the maximum source height is 200 m. and the corresponding frequency is 3 MHz, a high frequency for a ground wave but possible for a pulse close to the network. Atmospheric refraction would enhance the conductivity

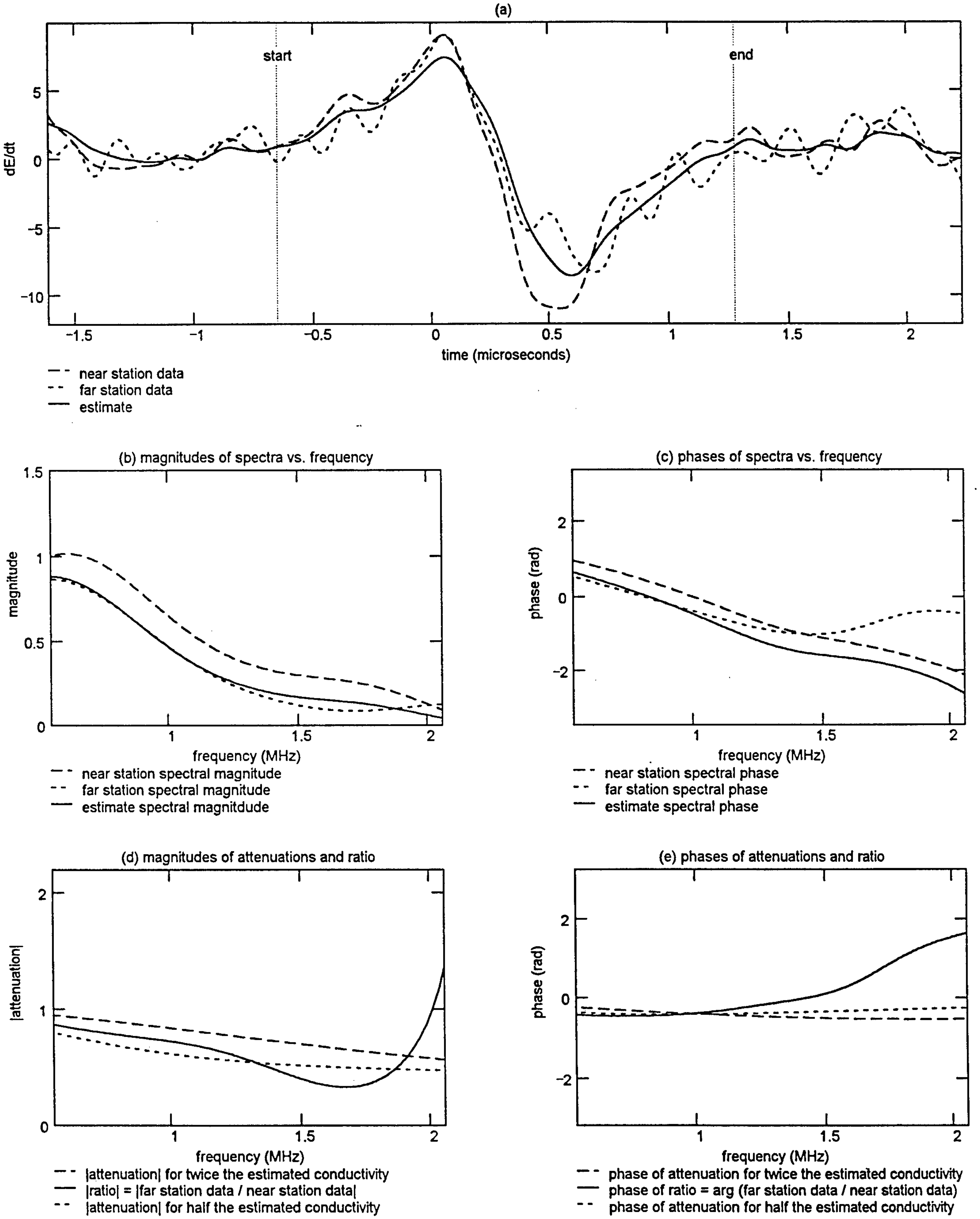

Fig 4. (a): Window showing subwindow limits, near station data, far station data, and estimate; (b) magnitudes of corresponding spectra; (c) phase shifts of spectra; (d) magnitudes of ratio of far station data to near station data and theoretical attenuation for twice the conductivity and half the conductivity; and (e) phase shifts of ratio and theoretical attenuation. System time tag = (1761.009 -1992 -254 -20 -31 -43 -608 -17) (Thomson, et al., 1994); station 2 time_tag = 499 ; near_station = 5 ; propagation distance to near station over land = 6147 m., far station = 3 ; difference in propagation distances over ground = 7223 m., and σ = 0.0058 S/m. All vectors were padded. This solution included data from all five stations.

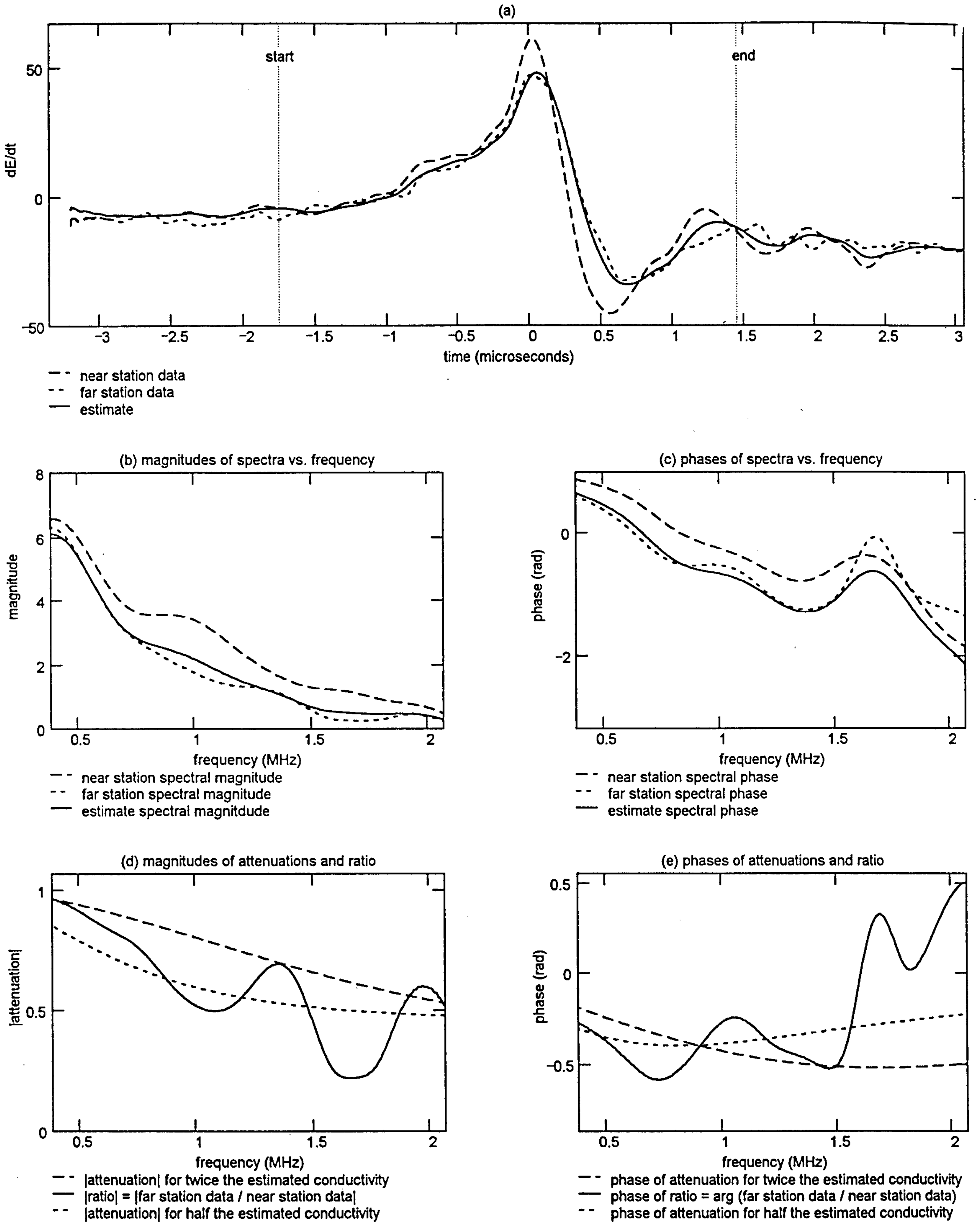

Fig. 5, (a): Window showing subwindow limits, near station data, far station data, and estimate; (b) magnitudes of corresponding spectra; (c) phase shifts of spectra; (d) magnitudes of ratio of far station data to near station data and theoretical attenuation for twice the conductivity and half the conductivity; and (e) phase shifts of ratio and theoretical attenuation. System time tag = (1761.009 −1992 −254 −20 −31 −43 −608 −17) (Thomson, et al., 1994); station 2 time_tag = 714 ; near_station = 5 ; propagation distance to near station over land = 6147 m., far station = 3 ; difference in propagation distances over ground = 7223 m., and σ = 0.0047 S/m. All vectors were padded. This solution included data from all five stations.

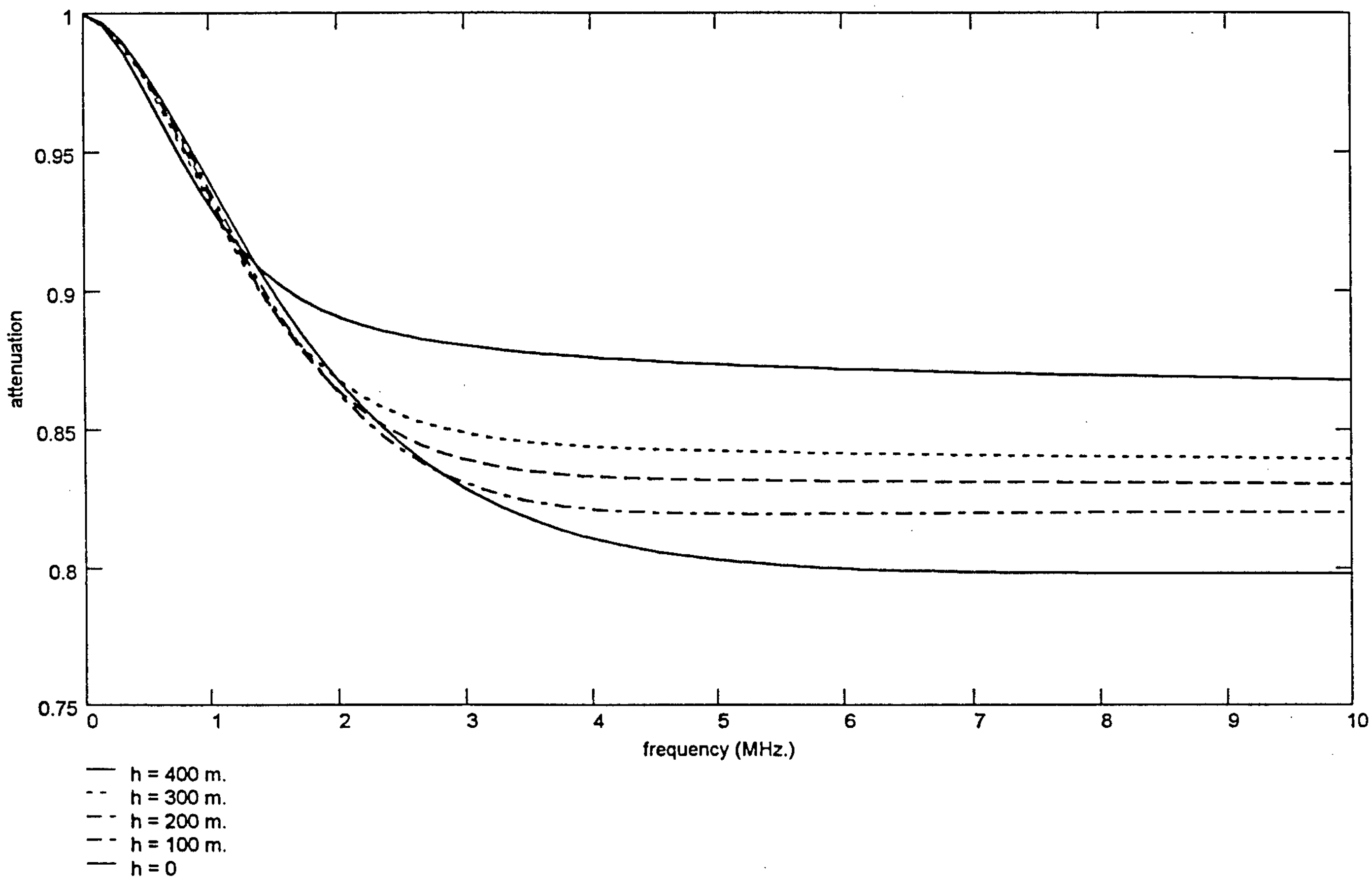

Fig. 6 (a). Attenuation due to ground conductivity = 0.004 S/m vs. frequency for five heights near ground and for d_n = 3 km. and d_f = 3.8 km. A soil moisture content of 26% was assumed.

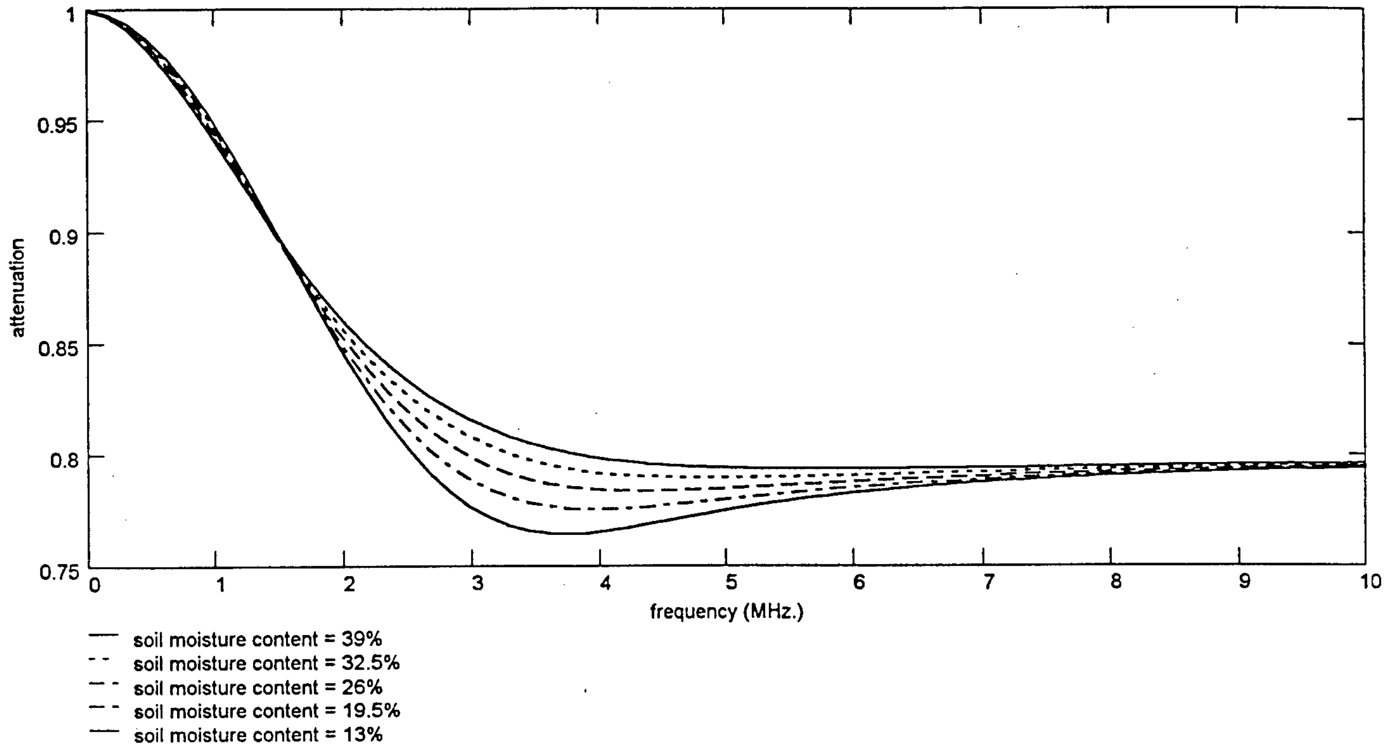

Fig. 6 (b). Attenuation due to ground conductivity = 0.008 S/m vs. frequency for five different soil moisture contents, for zero height, and for d_n = 6 km. and d_f = 7.5 km.

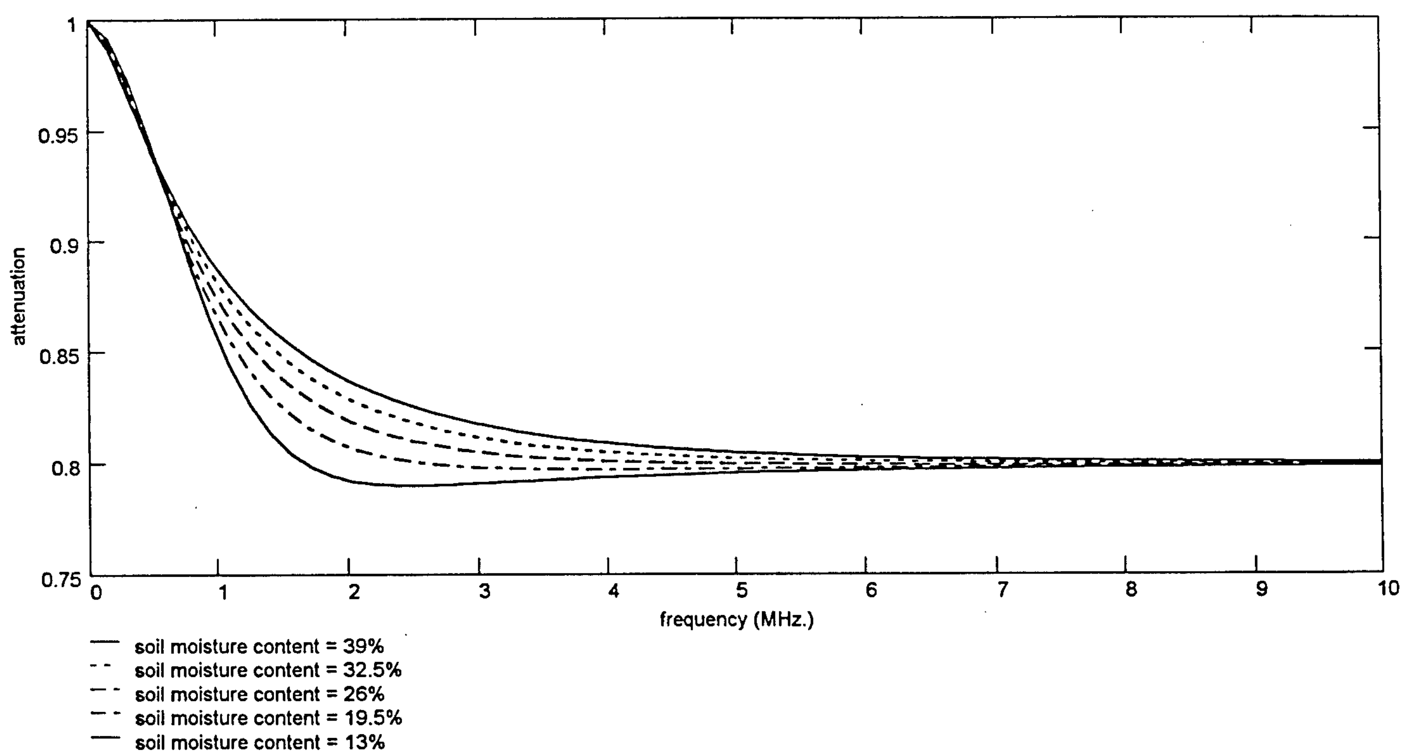

Fig. 6 (c). Attenuation due to ground conductivity = 0.002 S/m vs. frequency for five different soil moisture contents, for zero height, and for d_n = 6 km. and d_f = 7.5 km. The soil moisture content was assumed to be 26%.

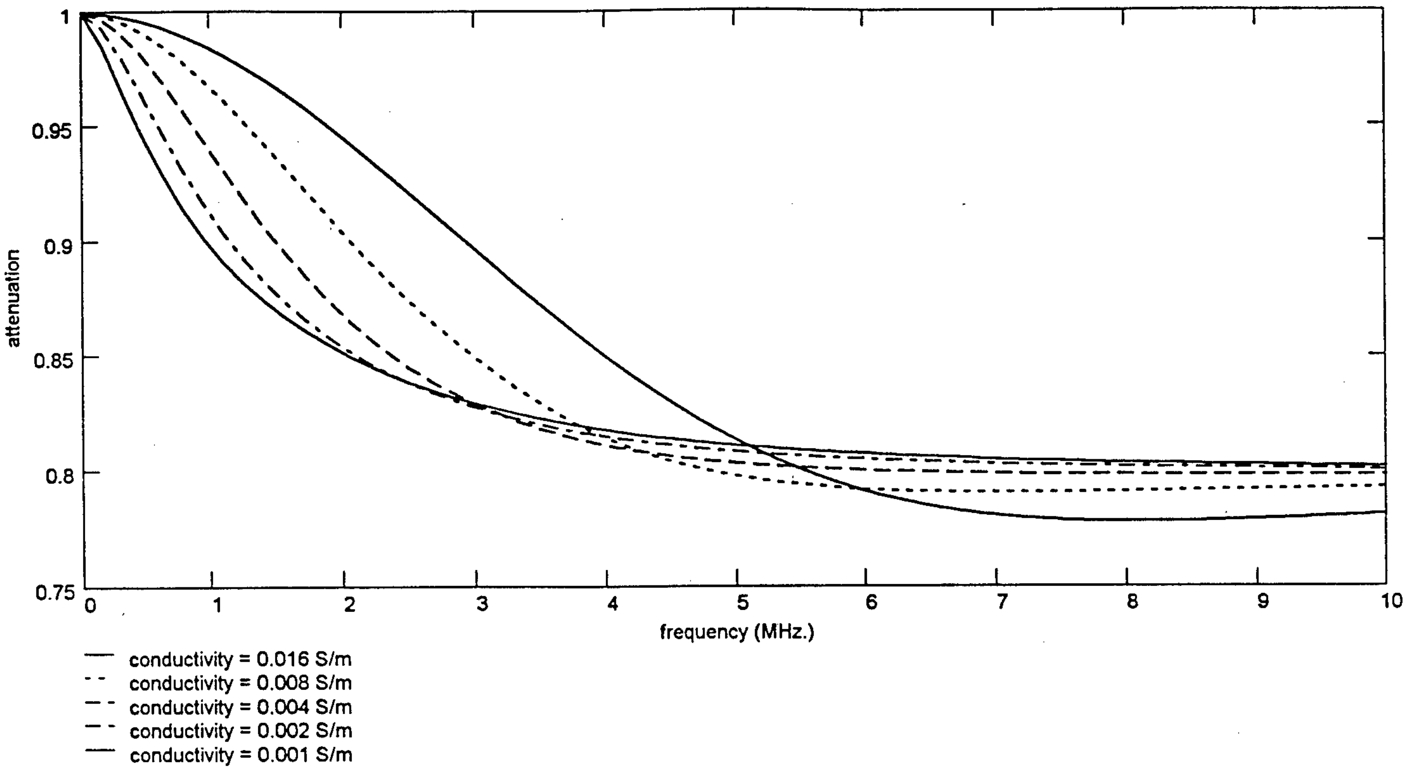

Fig. 6 (d). Attenuation due to five different ground conductivities vs. frequency for zero height and for propagation distances $d_n = 3$ km. and $d_f = 3.8$ km. The soil moisture content was asssumed to be 26%.

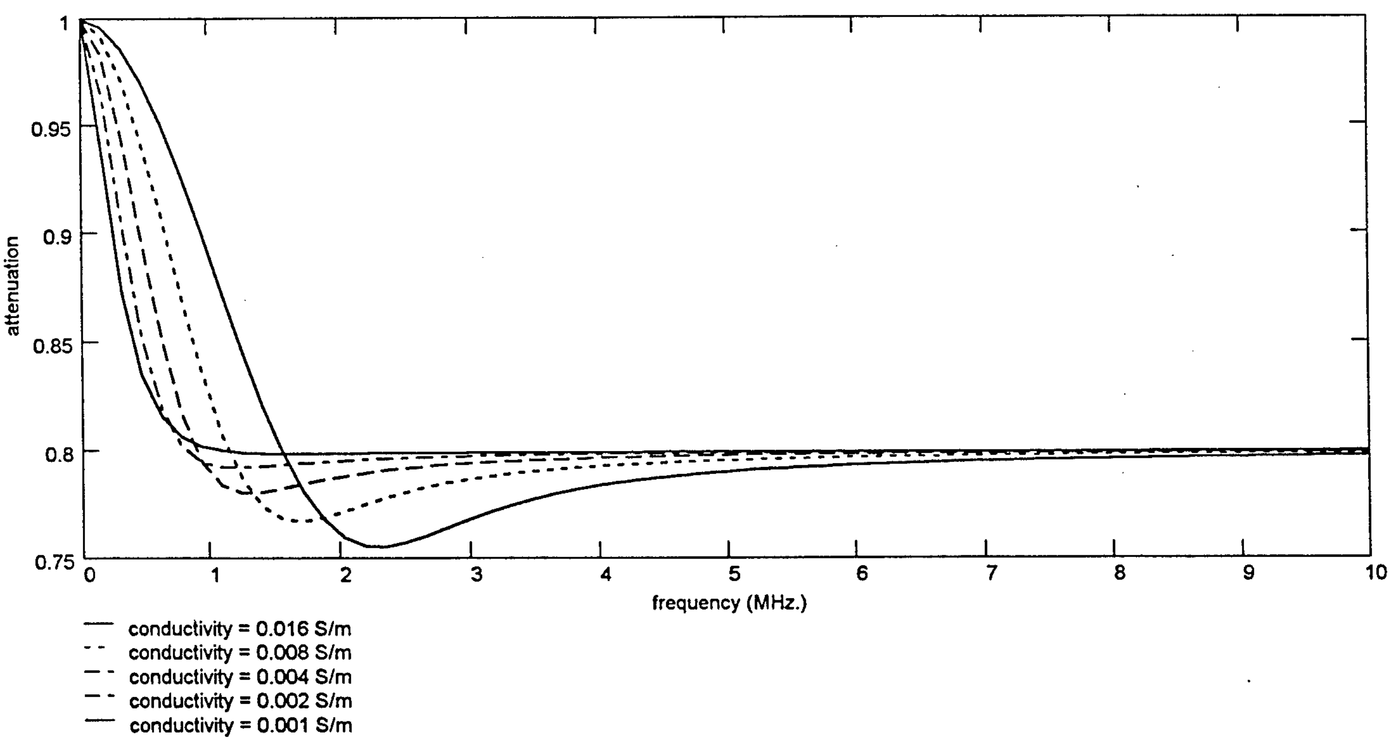

Fig. 6 (e). Attenuation due to five different ground conductivities vs. frequency for zero height and for propagation distances $d_n = 30$ km. and $d_f = 37.5$ km. The soil moisture content was assumed to be 26%.

effect on fields of distant sources within 200 m. of ground, further reducing any nonzero height effect on conductivity estimates.

Le Vine et al. (1986) simulated radiation electric fields resulting from a tortuous channel for which separate turn-on and turn-off terms were assumed at each kink in the channel, but the simulated channel was nearly vertical near ground. Working backward from the Le Vine et. al (1986) simulated waveshapes, the ground conductivity estimate was only about 20% lower if zero height was assumed, and this was for a maximum height of the channel of 1128 m., much higher than any herein

Variation in soil moisture content (discussed below) affects the dielectric constant $K = \frac{\varepsilon}{\varepsilon_0}$ (Smith-Rose, 1933; Hoekstra and Delaney, 1974), but dielectric constant variation has less effect on the attenuation function G at ground wave frequencies than conductivity variation, especially for higher conductivities (Fig. 6(b) vs. 6(c)). The dielectric constant can affect attenuation estimates around the fundamental frequency of some lightning pulses; for example, compare at 1.5 MHz. the attenuation curves of Fig. 6(c) (σ = 0.002 S/m) vs. those of Fig. 6(b) (σ = 0.008 S/m). Ground conductivity has a major effect on attenuation at low frequencies, per Fig. 6(d), but extending the propagation distance compresses the frequency band showing the effect; compare Figs. 6(d) and 6(e).

If the method described below were used to estimate di/dt then the estimates would be proportional to dE/dt under the assumption of a transmission line model (Uman, et al. 1975) so the di/dt estimates would be affected by ground losses (Cooray, 1989).

METHOD

Historically, conductivity has been estimated via field strength variation at a single frequency (e. g., Fine (1954) for 7000 radial paths from AM broadcast band radio stations throughout the continental U. S. and Burrows (1937) for 150 MHz. measurements on Seneca Lake, N. Y.), and via both high frequency loss and field strength variation of wideband lightning electric fields per Johler and Lilley (1961, two lightning pulses in midwest). The method we used was a variant of the latter method, the main difference being the use of a computerized gradient method to estimate the conductivity by minimization of sums of squares of measurement residuals.

We selected sharp unsaturated return stroke pulses and stepped leader pulses near ground in order that the maximum attenuation effects due to finitely conducting ground formulated in (1) by Sommerfeld (1909, 1926) would be observed. . Frequency normalization filters (Thomson et al., 1994) were applied to the data to remove the effects of unequal station responses. Lightning locations and times of occurrence (time tags) were computed per Thomson, et al. (1994) in the manner of a time of arrival system. Propagation distances were calculated manually (U. S. D. A., 1974, pp. 12-47, soil legend, guide, index, and map sheets 2, 6-8, 10-13, 14-18, 21-23, 26-29, 32-35, 37-40, 42-45, and 47-49). Disjoint stretches of land were lumped; so were disjoint stretches of sea. The approximate zero levels of the pulses were estimated using data from the beginning of each 200 microsecond event up to the last time tag (Thomson, et al., 1994). These biases were removed. Then the bias removal was repeated for the zero level computed without including any two sigma amplitude outliers (pulses, spikes, noise, etc). A systematic sinusoid associated with the instrumentation was removed from the station 2 data. The error model coefficients were estimated by minimizing the sum of squares of the measurement domain residuals via a gradient method (MathSoft, Inc., 1995). The data were time aligned with the far station time tag (Thomson, et al., 1994). The pulse widths extending from about the zero level before the peak to about the zero level after the overshoot were computed. The pulse widths delineated the subwindow for weighting the measurement residuals. If different station subwindows did not coincide then the narrowest subwindow was used. A rectangular window of length 2^n, where n is an integer, was picked around this time tag to include the subwindow. The windowed data were selected for digital signal processing. The subwindow width was increased if points immediately outside the limits of the subwindow were closer to the zero level than those at the limits. Data for station pairs were not processed if kR_1 did not exceed 20 for the period of the subwindow, i. e., if the pulse was not in the far field, or if the instrumentation was saturated. The dielectric constant was computed as a function of frequency (Smith-Rose, 1933; Hoekstra and Delaney, 1974). The complementary error function erfc(z) was computed from formulas found in Abramowitz and Stegun (1964, formula 7.1.5, p. 297, and formula 7.1.14, p. 298).

Initial estimates of error model coefficients were as follows: a ground conductivity 0.008 S/m was assumed (Fine, 1954); and $\binom{5}{2} = 10$ independent time shifts were estimated as the displacement of the pulse peaks, to the nearest sample point, for each pair of stations. Five time shifts, one per station, were estimated from the ten independent time shifts using the gradient method to minimize the sum of the squares of the time domain measurement residuals. Then more accurate estimates of the conductivity and time shifts were made using the gradient method to minimize residuals of zero mean (to prevent gradient method lockup at a local minimum) data and estimates which had been normalized by their RMS values. These were within a few per cent of the final conductivity values and comprise the conductivities reported herein unless otherwise mentioned. These may have been affected by subwindows which were too wide before the pulses and by system noise because the aforementioned zero phase lowpass filters were not used and because only the farthest station data were compared with the four other transformed station data vice making all ten pairwise station data comparisons. In the matter of making all ten pairwise comparisons of the data of the five stations, ten independent pulse amplitude calibrations were initially estimated as the RMS ratios of the far station data to the estimates; then, the five station gains were estimated from the ten corrected for $\frac{1}{\rho}$ spreading losses and five source amplitude estimates via the gradient method minimization of the sum of the squares of the time domain residuals.). The very small DC offsets were estimated as zero because estimating the biases exactly did not inject enough random noise into the process to allow the process to converge without reaching a local minimum. The sum of the squares of the time domain measurement residuals (differences between far station data and estimates) was minimized via the gradient method to estimate station gains and biases and to reestimate conductivities and time shifts. All conductivities for which the above process converged were tabulated. The process was considered to have converged if varying the conductivity +_20% from the estimate and calibrating out the other error model coefficients caused the sum of squares of measurement residuals to increase, indicating a local minimum.

Assumptions and approximations included the following: the ground was linear, isotropic, and homogeneous; the earth was flat in the neighborhood of KSC; air had the electrical properties of vacuum for ground wave propagation; the source heights were zero; the propagation effects over seawater or brackish water were negligible; fresh water could be lumped with finitely conducting ground; the effects of lumping short (less than a wavelength) stretches of like media (either land or seawater) could be ignored, the dielectric constant was a piecewise continuous function of frequency (Hoekstra and Delaney, 1974) but the moisture content was constant at 26% (Smith-Rose, 1933); and effects on conductivity estimates of smaller interfering pulses were negligible. Atmospheric and coastal refraction were ignored. For 10 kilometers of propagation over seawater having 4 S/m conductivity the amplitude loss was estimated to be less than 0.3% at 1 MHz and less than 3% at 4 MHz by a method of King and Wait (1976, eq. (4.16), p. 171, to duplicate Fig. 4.4, p. 173) and the time shift was only about 15 nanoseconds.

As a check of the above procedure, we duplicated previous curves of attenuation vs. height for several frequencies (Le Vine et al., 1986, Fig. 11, p. 11,905); then, found the conductivity using the waveshape differences (Le Vine et al., 1986, Fig. 8, p. 11,902, right). The small tortuousity of the first part of the lightning channel was ignored. A gradient method was used to minimize residuals in the frequency domain (Mathcad PLUS 6.0 (MathSoft, Inc., 1995) version of the MINPACK-1 (More, et al., 1980) implementation of the Levenberg-Marquardt gradient method). Estimating conductivity for the average height of source (564 m., based on the assumed return stroke velocity and the time midpoint of the data, we found the same value (0.0050 S/m) as that originally assumed by Le Vine et al., 1986. The ground conductivity estimate dropped from 0.0050 S/m to 0.0041 S/m if zero source height was assumed. Another check was duplication of Fig. 5 of Burrows (1937) wherein an error of Norton (1936) was noticed. The error has been reported by Trainotti and Marco (1992).

RESULTS

The histogram of conductivity values in Fig. 7 was obtained from 31 dE/dt pulses recorded on September 10, 1992 in which 96 (83%) of a possible 115 . In the appendix, we give the specifications for the sources of these pulses (file number, time of occurrence, location). Note the roughly log normal distribution of this histogram consistent with Fine's (1954) analysis of Kirby's (1954) ground conductivity estimates. The table below further classifies these 96 points into sources from stepped leader pulses and return strokes.

lightning process	no. of points	median (S/m)	geom. mean (S/m)	geom. s. d. (no units)
stepped leader	37	0.0048	0.0051	2.25
return stroke	59	0.0042	0.0043	1.79
total	96	0.0042	0.0046	1.98

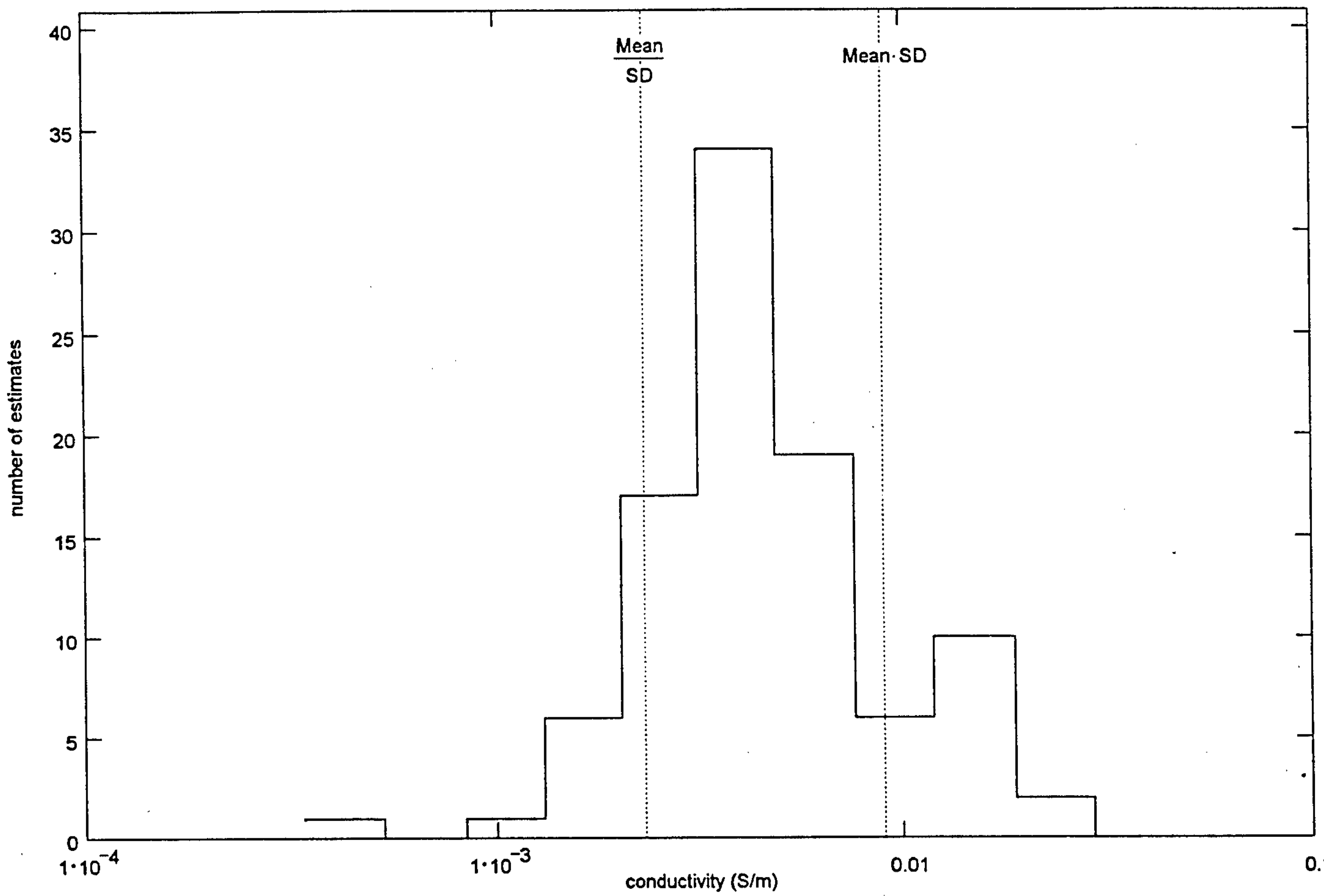

Fig. 7. Histogram of measured ground conductivities: N = 96 points, geometric mean = 0.0046 S/m, geometric standard deviation = 1.98 , median = 0.0042 S/m, minimum_conductivity = 0.0005 S/m, maximum_conductivity = 0.0238 S/m.

A more detailed analysis of two pulses that occurred consecutively in time in the same lightning – the final stepped leader step followed by the return stroke – is of value since for these pulses we would expect to find the same conductivity. Indeed, for the two cases where estimates were obtained (stations 3 and 4) the values are in good agreement, and certainly much less than the factor of 2 in the overall histogram.

consecutive pulse type	height (m)	conductivity (S/m) associated with far station (sta. 5) 1	2	3	4
stepped leader	est. 100	*	0.0011	0.0032	0.0038
return stroke	est. 0	0.0105	*	0.0025	0.0039

*no solution

Conductivity estimates made with all ten pairwise comparisons at one for these two pulses were 0.0058 S/m and 0.0047 S/m, respectively, when the model estimated single ground conductivity. Figures 4 and 5 shows the widening and attenuation of the pulse due to conductivity (plots (a)), corresponding amplitude (plots (b)) and phase (plots (c)) spectra with ideal attenuation per Sommerfeld (1909, 1926) for the station pair (3, 5). Note the conductivity effects on the pulse peaks (lower), overshoots (higher), and widths (wider; Fig. 4 (a) and 5(a). The envelope of the two attenuation curves for half the conductivity and twice the conductivity are given in Fig. 4 (d) and Fig. 5 (d) as a qualitative indicator of the error limits in the conductivity.

ERRORS

Analysis of variance for two-way classification of conductivity grouped by lightning location and by station rejected the null hypothesis that all data grouped by station were associated with the same conductivity distribution. Refer to Fig. 8 for location of locations of lightnings, groups of lightnings, and stations. The y-axis is North and the x-axis East, as shown in Fig 1. The lowest geometric standard deviation of conductivity (1.35) was for station 4, which happens to be the most landlocked station.

In order to identify the conductivity variance attributable distance, dielectric constant and height errors, we calculated these errors numerically using estimates of errors in distance, dielectric constant, and height and calculating $\delta\sigma^2 = \delta\sigma d^2 + \delta\sigma h^2 \delta\sigma K^2$, where $\delta\sigma d^2, \delta\sigma h^2$, and $\delta\sigma K^2$ are variances in conductivity due to variations in distance, height, and dielectric constant, respectively and $\delta\sigma^2$ is the total variance. The estimates were:

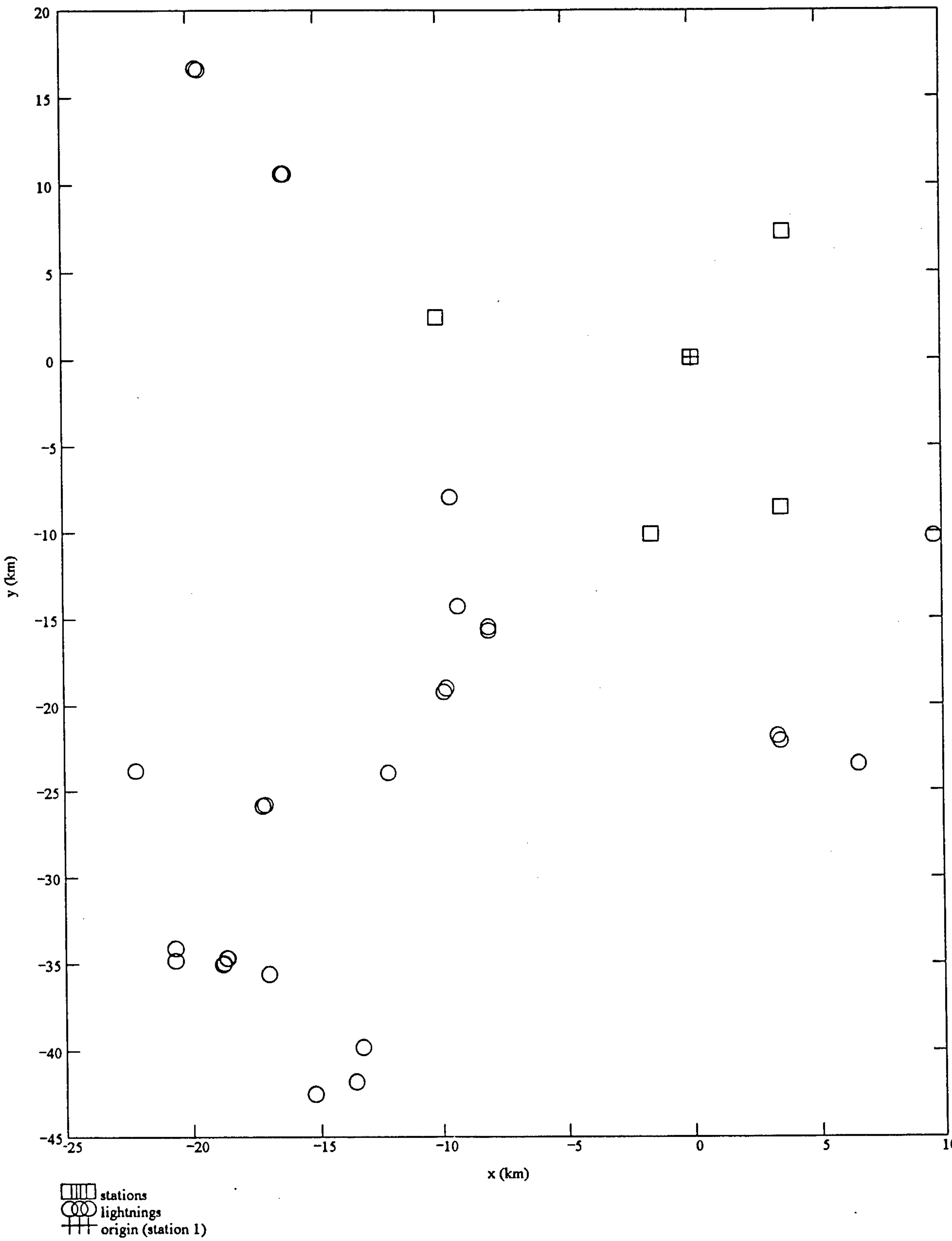

Fig. 8. Measurement station and lightning locations.

source of variance	symbol of variance	median variance (S^2/m^2)
distance	$\delta\sigma^2$	0.005×10^{-6}
height	$\delta\sigma h^2$	0.003×10^{-6}*
dielectric const.	$\delta\sigma K^2$	0.11×10^{-6}
total	$\delta\sigma^2$	0.14×10^{-6}

* $\delta\sigma h^2$ is only half this value for return stroke only

Since $\frac{\delta\sigma}{\sigma}$ was log normally distributed with geometric mean = 8.0 % vs. geometric standard deviation = 2.0 in the overall conductivity distribution we conclude that errors arising from uncertainty in distance, height, and dielectric constant are insignificant.

The variances $\delta\sigma d^2, \delta\sigma h^2$, and $\delta\sigma K^2$ were estimated under certain assumptions. Assuming that the maximum stepped leader velocity was 10^7 m/s, the maximum height error would be 100 m. for any stepped leader pulse occurring within 10 microsec. of a return stroke. Assuming a 0.25" (125 m.) map accuracy per propagation path (USDA, 1974, map sheets 2, 6-8, 10-13, 14-18, 21-23, 26-29, 32-35, 37-40, 42-45, and 47-49), a 0.25" map reproduction and paste-up accuracy, a 0.25" human map reader accuracy per path, and lightning location system range errors of 30 -45 m. (Thomson, et al., 1994), the range errors were approximated. The dielectric constant error was based on a U. S. D. A. (1974, pp. 12-47) observation that land in and around KSC is mostly poorly drained and level and/or has a water table which could affect the conductivity estimate (Wait, 1981, p. 11) so that it could be similar to English soil. It seemed reasonable that the nominal dielectric constant for 26% soil moisture content could be assumed, and that a maximum water content of 39% could be assumed, so that a standard deviation of water content of ±6.5% from 26% could be assumed, judging from an evenly spaced family of curves of dielectric constant vs. soil moisture content for sites in England (Smith-Rose, 1933).

Band limited system noise was observed for all five stations. The noise spectra appeared similar for stations 2, 3, 4, and 5, which had 4 MHz. bandwidths and smaller in amplitude for station 1 which had a 2 MHz bandwidth. The question arose: could conductivity variance have been attributable to this band limited system noise? To help provide an answer, the estimated far station data plus many sections of detectable-pulse-free noise from the same event were substituted for the far station data for four pulses suspected of being most sensitive to noise and the conductivity was reestimated as many times for each pulse. The amplitudes of the station data could reach ±127 before the instrumentation would saturate. Results were as follows:

pulse no. (event/ station 2 time tag/ near station/ far station)	peak pulse ampl.	best conductivity est. (S/m)	no. of noise est.	RMS noise ampl.	conductivity geom. mean (S/m)	conductivity geom. s. d.
25402705.005/ 1368/ 4/ 5	38	0.0049	40	0.7	0.0048	1.05
25400014.012/ 148/ 3/ 4	49	0.0095	34	1.5	0.0094	1.11
25402414.010/ 464/ 1/ 3	38	0.0023	25	0.7	0.0022	1.64
25401761.009/ 499/ 5/ 3	7	0.0025	28	1.4	0.0019	1.69

Although the geometric standard deviation due to noise (last column) did not account for all of the conductivity variance, it begged that conductivity be estimated by minimizing the sums of the squares of the measurement residuals for all ten possible combinations of stations at one. Results were:

pulse no. (event/ station 2 time tag)	best conductivity est. (S/m)	no. of est.	no. of close pariwise matches	did single pair compared above still match closely?
25402705.005/ 1368	0.0044	1	9/10	yes
25400014.012/ 148	0.0193*	1	1/10	no*
25402414.010/ 464	0.0022	1	7/10	yes
25401761.009/ 499	0.0058	1	6/10	yes

*process did not converge

The noise effect on the conductivity estimate was largest for the smallest amplitude pulse (last line above; amplitude = 7). A plot of standard error of estimate vs. amplitude showed this trend (Fig. 9).

DISCUSSION

Fine (1954) used the data of Kirby (1954) to estimate a single ground conductivity per path mostly over paths of length 25 km. or less, with 18 to 20 measurements per path. The paths used herein were 0.8 to 37 km over land, 4 to 23 km. over seawater, and 7 to 53 km. total. The difference in propagation distances between stations was limited by the maximum distance across the five-station network, which is about 18 km. including the seawater.

Kirby (1954) wrote, "Because the characteristics of the ground may vary considerably with depth, the values of effective ground conductivity presented herein strictly apply only at the frequencies at which the measurements were made." Thomson et al. (1988) measured the ground conductivity at one site at KSC via the Wenner four-probe method at depths:

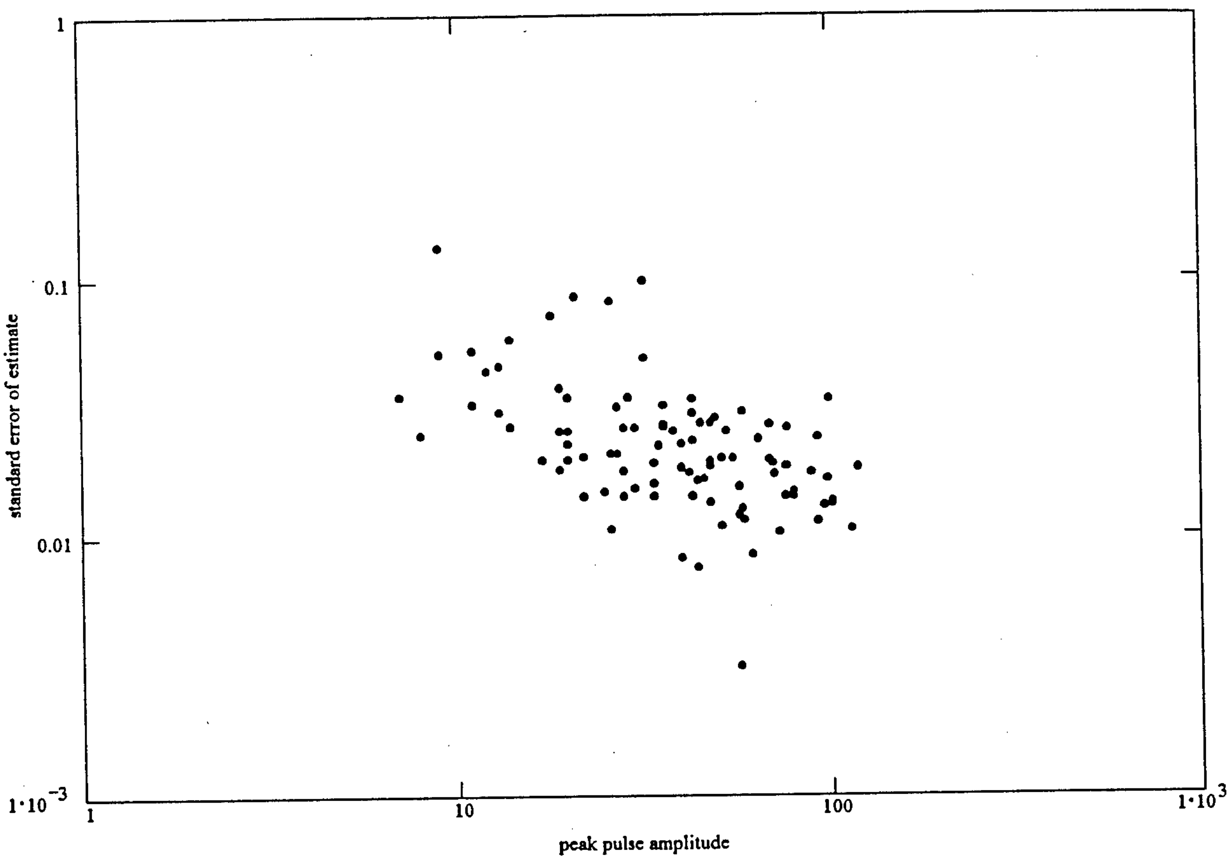

Fig. 9. Log-log plot of standard error of estimate vs. peak pulse amplitude shows inverse relationship between error and signal strength.

depth (m.)	conductivity (S/m)
0 to 2.2	0.0082
2.2 to 11	0.031
11 to 40	0.200
below 40	0.0025

According to equation (4) the depth for which conductivity of 0.0081 S/m would be affected by conductivity of an underlying layer is 15 meters, so the estimates of effective ground conductivity herein were affected by the higher conductivities of lower layers.

Fine (1954) observed that "...approximately two-thirds of the measured path conductivities for a typical subsoil type lay within the range of 1/1.85 and 1.85 times the subsoil median conductivity. Grouping these subsoil types into parent soil groups gave so large a standard error that this approach was abandoned" and that "...measured conductivities for paths over the same terrain often varied by more than 2 to 1, depending upon direction, frequency, interpretation, equipment, etc. Since the measured effective conductivity varies more than this amount in many cases and because of a standard error of 1.85 to 1 for subsoil types, it was decided that there was no point in having a conductivity map with classifications closer together than 2 to 1." Fine chose conductivity classes of 0.5, 1, 2, 4, 8, 15, and 30 mS/m for land. Most of Brevard County, Fla., including KSC, was included in the 0.008 S/m conductivity class on Fine's (1954) map. Soil types of Brevard County, Fla. are not a single subsoil type (U. S. D. A., 1974, p. 12); i. e., "the St. Johns River Valley is made up of marsh, sandy prairie, and flatwoods"(U. S. D. A., 1974, p. 1). Salt water (including seawater, brackish water, tidal marsh, tidal swamp, and most submerged marsh) covers about 22.5% of the county, fresh water covers 8.5%, including swamp and ponded or flooded sands or soils, and the rest is covered by various types of sand and sandy soils (49.9%), peat (7.2%), muck (4.4%), urban land and urban complex (4.2%), soils (2.2%), complex (1.8%), and borrow pits and sanitary landfill (about 0.1%). Summers are humid and account for 65% of rainfall; much of the soil is poorly drained (U. S. D. A., 1974, "Climate," p. 2; and "Descriptions of the Soils," pp. 6-48, respectively). A 0.002 S/m conductivity area is north and west of Brevard County (U. S. D. A., 1974, p. 1), but there is no intermediate class of 0.004 S/m in Fine (1954) which would be closer to the mean conductivity herein of 0.0047 S/m than either of Fine's (1954) arbitrary class choices 0.002 or 0.008 S/m.

SUMMARY

Waveshapes of dE/dt of lightning ground waves were recorded at a 15 km. baseline network of five stations at KSC in 1992. Ground constants (conductivity and dielectric constant) were subsequently modeled and a digital computer was used to estimate 96 ground conductivities based upon differences in waveshapes alone. Pairwise comparisons of waveshapes with the furthest station waveshape were made one at a time. Not all of the conductivity variation was attributable neither to system noise nor to errors in source height nor ground constants, although system noise was a major source of error. The null hypothesis that stations were associated with the same distribution of ground conductivities was rejected. Conductivity values were in line with published values. Comparisons of all ten combinations of station data at one yielded station gain estimates and reduced variation among conductivity estimates due to noise.

CONCLUSION

Since the soil of Brevard County is not a single type, the standard deviation of conductivity estimates could reasonably be expected to exceed 1.85 and to be about 2.0; therefore, the conductivity estimates for the events herein are comparable to Fine's (1954) conductivity estimate of 0.008 S/m with geometric standard deviation of about 2.0.

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Stephen M. Davis selected many pulses and computed time tags per Thomson et al. (1994).

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APPENDIX

Thirty-one lightning pulses were chosen from 23 files. The computation process converged for 96 of the 124 possible conductivities (four stations times 31 pulses).

pulse no.	file	year	day	hr	min	sec	ms	μs	x (m)	y (m)	z (m)
1	25400014.007	1992	254	19	12	17	617	183	19613.0119	16588.7087	356.0676
2	25400014.012	1992	254	19	12	18	25	96	19699.7144	16660.601	214.5793
3	25400014.013	1992	254	19	12	18	182	59	19678.0972	16659.9879	379.6275
4	25400223.02	1992	254	19	25	9	818	1	16251.5641	10596.2976	330.5921
5	25400223.02	1992	254	19	25	9	818	1	16213.9005	10576.072	320.6562
6	25400223.02	1992	254	19	25	9	818	1	16328.0857	10630.3261	439.6077
7	25401408.007	1992	254	20	17	0	848	25	9283.0074	14350.3661	138.4288
8	25401478.009	1992	254	20	19	53	768	28	9585.0202	7959.1259	505.0381
9	25401672.007	1992	254	20	27	56	636	366	8097.0858	15734.8531	228.0096
10	25401672.007	1992	254	20	27	56	636	366	8067.3121	15559.538	24.3057
11	25401761.009	1992	254	20	31	43	608	17	9767.2285	19041.046	425.0809
12	25401761.009	1992	254	20	31	43	608	17	9901.9099	19290.1151	154.1564
13	25401824.025	1992	254	20	34	49	94	7	17248.2813	25868.9823	89.8953
14	25401824.025	1992	254	20	34	49	94	7	17164.3212	25747.7005	14.645
15	25402167.006	1992	254	20	51	54	666	93	17061.4999	35570.6882	218.1696
16	25402167.008	1992	254	20	51	54	875	872	20709.9044	34138.6284	29.59
17	25402188.001	1992	254	20	52	49	832	277	18800.9176	34974.2582	232.3092
18	25402188.003	1992	254	20	52	49	878	35	18688.0046	34719.972	172.144
19	25402188.004	1992	254	20	52	49	898	35	18670.2642	34688.4693	163.2644
20	25402188.006	1992	254	20	52	49	989	314	20687.6952	34796.2462	499.8297
21	25402188.007	1992	254	20	52	50	64	2	18866.8777	35045.3377	125.7637
22	25402414.01	1992	254	21	2	46	162	207	22212.052	23784.557	235.2703
23	25402504.011	1992	254	21	6	24	438	10	13319.1345	39858.9442	263.2395
24	25402510.004	1992	254	21	6	49	956	872	15245.5269	42554.7575	459.587
25	25402540.015	1992	254	21	8	5	667	98	12174.0515	23969.1467	323.2715
26	25402705.005	1992	254	21	15	59	132	783	3336.4079	21825.5169	380.4738
27	25402705.005	1992	254	21	15	59	132	783	3405.3242	22114.5837	420.2764
28	25402814.007	1992	254	21	21	29	508	6	13599.0102	41794.9289	241.4365
29	25402979.011	1992	254	21	29	36	308	12	9680.1821	10211.4188	141.0551
30	25402979.013	1992	254	21	29	36	337	353	6521.4563	23451.4094	781.5232
31	25402979.022	1992	254	21	29	36	372	575	9162.7895	9911.1408	192.7055